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Physical design and performance estimation of heterogeneous optical transmission systems

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Abstract

This article introduces the issues of design and estimation of performance of a heterogeneous optical transmission system, taking into account the multiplicity of physical effects impairing propagation simultaneously, and, most particularly, the impact of Kerr-induced non-linear effects. We review the usual engineering tools enabling us to predict system performance, as well as design tools to optimize dispersion-management. Finally, we introduce the concept of weighted non-linear phase shifts, to capture the impact of the accumulated non-linearities on a propagating signal, and derive analytical expressions for system reach and power optimization in the context of highly heterogeneous optical link with mixed fiber features. ***To cite this article: J.-C. Antona, S. Bigo, C. R. Physique 9 (2008).***

Résumé

Conception et estimation de performance d'un système de transmission optique hétérogène. Cet article aborde les problématiques de la conception et l'estimation de performance d'un système de transmission optique hétérogène, prenant en compte la multiplicité des phénomènes physiques interagissant, et tout particulièrement l'impact combiné des effets non-linéaires de type Kerr et de la dispersion chromatique. Nous passons en revue les grandes classes d'outils de design utilisés pour prédire la performance d'un système, ou pour optimiser la gestion de la dispersion chromatique. Enfin, nous introduisons les concepts de phase non-linéaire pondérée qui capturent l'impact de l'accumulation des effets non-linéaires sur le signal se propageant, et en déduisons des expressions analytiques prédisant la portée d'un système, ou permettant d'optimiser les puissances dans le contexte d'un réseau optique hétérogène composé de sections de fibres de caractéristiques très variables de l'une à l'autre. ***Pour citer cet article : J.-C. Antona, S. Bigo, C. R. Physique 9 (2008).***

Keywords: Optical fiber; Non-linear optics; Chromatic dispersion; System design; Dispersion-management; Telecommunication networks

Mots-clés : Fibre optique ; Optique non-linéaire ; Dispersion chromatique ; System design ; Gestion de dispersion ; Réseaux de télécommunications

1. Introduction

Over the last few decades, optical fiber has become the preferred medium for conveying data across cities, regions, nations, continents, oceans, owing to its very low attenuation and its very large bandwidth. Not only laboratory,

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but also commercial, Wavelength-Division Multiplexed (WDM) systems offer multi-Terabit/s capacity based on 10–40 Gb/s-modulated channels propagating at different wavelengths over more than a thousand kilometers [1] in order to cope with the increase of the data traffic [2,3]. Yet, efficiently designing high speed optical transmission systems or optical networks at lowest cost with ever increased throughput or reach is a big challenge; it requires very subtle knowledge of the interplay of multiple physical phenomena, and effective engineering rules to deal with the complexity of a whole system. Indeed, numerous physical effects of different natures can impact propagation over optical fiber links, such as fiber attenuation, noise, chromatic dispersion, Kerr effects, Polarization Mode-Dispersion, Stimulated Raman, Brillouin or Rayleigh scattering, linear/non-linear crosstalk, filtering… [4]. Besides, optical systems tend to become more and more heterogeneous: the fiber sections composing a transmission system can be of different lengths from one amplifier to another, following some constraints of geography or network topology, and even of different types, in order to cope with the need to reuse already installed fiber sections when building larger optical networks. Eventually, optical networks are expected to support different generations of systems, modulated at different bit-rates, and sometimes coexisting on a same fiber link [5]. For all those reasons, efficiently designing a complex, heterogeneous optical system while maximizing the reach of optical links is full of challenges: such challenges comprise on the one hand the selection of the optical, electronic and optoelectronic components involved and on the other hand an efficient way to combine them all, based on simple yet reliable rules allowing a fair general estimation of system performance.

In this article, we will first briefly describe typical terrestrial transmission systems and the major physical limiting phenomena. We will then explain how system performance can be predicted, and how a system can be designed, with a special focus on the management of optical non-linearities, using semi-analytical/semi-empirical models built from interactions between theory, system experiments and numerical simulations. More particularly, we will introduce the concepts of cumulated non-linear phase [6] and weighted non-linear phase [7,8] and demonstrate their relevance in capturing the impact of accumulated non-linearities in a dispersion-managed transmission system. We will then show possible applications of those tools for system reach prediction, systems or subsystem comparison, or for system design through setting rules of fiber input power, starting from homogeneous systems with all line-fiber sections being identical to highly heterogeneous systems supporting fiber sections of different lengths and types.

2. Basics on optical transmission systems and major impairments

2.1. WDM transmission systems

A basic digital optical transmission system consists of optoelectronic transmitters followed by an optical transmission link, and by optoelectronic receivers. The transmitter converts binary data into a modulated optical signal at a given bit-rate on a given optical carrier wavelength (usually denoted as a channel), that is sent into an optical transmission link. The transmission link is primarily composed of a concatenation of sections of single-mode optical fibers and optical amplifiers, and conveys the signal to an optoelectronic receiver, which recovers the binary information after photo-detection around the carrier wavelength and signal sampling.

The WDM (Wavelength Division Multiplexing) technique is based upon combining (multiplexing) into the same fiber N modulated channels, each being at a different carrier wavelength (Fig. 1). The total throughput is the sum of the individual channel bit rates, which are usually identical (e.g. throughput $= N \times 10$ Gb/s). At the receiver side, each channel is filtered and recovered separately, so that any limitations on fiber propagation arising from linear effects in the fiber, such as noise sensitivity, Group Velocity Dispersion and Polarization Mode Dispersion (PMD), are only related to the bit rate of each individual channel. WDM is therefore a very efficient and common way to exploit the large fiber bandwidth [9], and allow high-capacity and distance transmission of up to 164 channels modulated at 100 Gb/s over 2550 km, which corresponds to a capacity $\times$ distance product of 41.8 Pbit/s km [1,10].

2.2. Basic tools: BER, Q factor

We usually measure the quality of a transmission system using the Bit-Error Rate (BER), which is the ratio of erroneously transmitted bits over the total number of transmitted bits. Errors stem from signal distortions and optical/electrical noise. Optical links are expected to convey data with a BER as low as 10^{-13}. This has become possible over several thousands of kilometers owing to the use of Forward Error Correction devices, generally able to bring

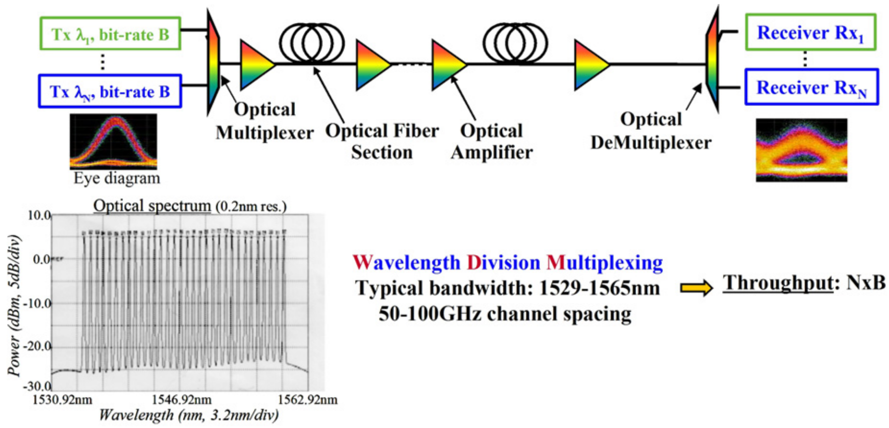

Fig. 1. Basic WDM transmission system.

BERs as high as 2×10^{-3} before correction, down to 10^{-13} BER after correction, with information redundancy of only ∼7% [11]. Measurements of BER are obtained by sending and receiving some known pseudo-random data, or by exploiting the error counters of the Forward Error Correction devices. This BER is often expressed in terms of Q factor, using the following conversion relationship [9,12,13]:

$$\mathrm{BER} = \frac{1}{2}\mathrm{Erfc}\left(\frac{Q}{\sqrt{2}}\right) \tag{1}$$

where Erfc() is the complementary error function. Q factor itself is generally expressed in dB scale, with $Q^2_{\mathrm{dB}} = 20\mathrm{Log}_{10}(Q)$. A BER of 10^{-3} thus corresponds to a Q factor of ∼10 dB. This expression in dB scale is used to maintain consistency with the linear noise accumulation model. For example, a 3-dB increase in the average launch power in all of the fiber spans results in an almost 3-dB increase in Q-factor, assuming that signal-spontaneous beat noise dominates and ignoring signal decay and fiber non-linearity. Besides, it is possible to obtain a direct analytic expression of the Q factor when the received symbols follow Gaussian distributions: in the case of basic Non-Return to Zero format, with possible marks "1" or spaces "0" detected, with mean intensities μ_1 and μ_0 respectively, and standard deviations σ_1 and σ_0 respectively, the Q factor is:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{2}$$

Hence, efficiently designing and operating an optical transmission system requires being able to predict accurately the quality of the link, generally through the BER. The system quality of transmission can be seen as a function of all the parameters describing each subpart of the transmission link. From a system point of view, we must identify a few key, synthetic parameters that rule system performance and correspond to macroscopic physical phenomena, and understand/quantify their impact. Let us first describe a few major physical phenomena, and their system impact.

2.3. *Major physical impairments*

Let us now briefly describe *the major physical impairments* and their influence on the design of usual transmission systems. For this purpose, we will start with the description of the propagation equation into an optical fiber (Non-Linear Schrödinger Equation) [4] (following the $(kz - \omega t)$ convention):

$$\frac{\partial A}{\partial z}(z,T) = -\frac{\alpha}{2}A - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + i\gamma|A|^2 A \tag{3}$$

where $A(z,T)$ is related to the complex envelop of the optical signal around carrier frequency ω, z refers to transmission distance, T refers to time in the retarded time frame (accounting for mean group velocity induced time shifts at distance z), α stands for fiber linear attenuation, β_2 for fiber Group-Velocity Dispersion, and γ for the non-linear Kerr coefficient.

2.4. Attenuation – noise

One limitation to system reach comes from *fiber attenuation*. Despite very low values of attenuation for wavelengths around 1550 nm, about 0.2 dB/km, long-haul transmission, over a few hundreds of kilometers or more, is not feasible without optical amplification or regeneration. Therefore, inline optical amplifiers, mostly Erbium Doped Fiber Amplifiers, are generally deployed along the transmission link, on average every 80 km for terrestrial systems. They can amplify an optical field over a wide waveband such as the C-band (between 1530 and 1565 nm) without optoelectronic regeneration, and therefore allow much longer transmission reach for all the transmitted channels in the amplified waveband, even though the amplifiers generate Amplified Spontaneous Emission (ASE) noise at the same time. After transmission over an amplified link, the accumulated ASE becomes the dominant source of noise, and the *Optical Signal to Noise Ratio* (OSNR) at the receiver end is the most relevant parameter to characterize noise-related system degradation: it refers to the ratio of the channel signal power divided by the optical noise power (integrated over reference bandwidth, usually 0.1 nm). OSNR is a cumulative parameter since the inverses of the OSNR degradations of different parts of the system can be added to get the inverse of the overall OSNR [9]. In order to quantify system *tolerance* to noise, we usually define the OSNR sensitivity as the required OSNR to guarantee a reference Bit-Error Rate. If we choose this reference BER equal to the one corresponding to the feasibility of optical connections, therefore an optical connection will hence be feasible as long as the actual OSNR at receiver end is higher than the OSNR sensitivity. To do so, a minimum input power into fiber sections is required. Typical OSNR sensitivity (assuming reference 0.1 nm noise bandwidth) is about 13 dB for a 10^{-5} BER in 10 Gb/s Non-Return to Zero systems, and scales proportionally with the inverse of the bit-rate (with OSNR in linear scale).

To account for non-noise system impairments, the notion of *OSNR penalty* is often used: for a reference BER, it represents the excess OSNR required after transmission to get this reference BER, with respect to the requirements in the so-called "back-to-back" configuration, i.e. when transmitter and receiver are directly connected, without transmission. In other words, the OSNR penalty is the difference in sensitivity (in dB scale) after and before transmission for the same reference BER.

2.5. Chromatic dispersion

Another limitation stems from Group Velocity Dispersion (GVD), also referred to as *chromatic dispersion*. GVD characterizes wavelength dependence of fiber refractive index $n(\lambda)$. It is the linear phenomenon by which the spectral components of a signal are carried by guided modes which have different speeds. They therefore arrive delayed with respect to each other at the receiver end, thus distorting the original signal waveform and increasing the number of decision errors. Fiber GVD is usually characterized with the dispersion parameter per unit length expressed in ps/(nm km). The typical dispersion characteristics of the two most widely available fiber types are 17 ps/(nm/km) at 1550 nm for standard SMF (Single-Mode Fiber, G652 type according to ITU-T (International Telecommunication Union – Telecommunication) standardization body) and 4 ps/(nm/km) at 1550 nm (2.6 ps/(nm/km) at 1530 nm) for LEAF^{TM} fiber (Large-Effective Area Fiber, G655 Non-Zero Dispersion Shifted Fiber type). The net impact of chromatic dispersion after propagation naturally depends on the *accumulated dispersion* (ps/nm) along all fiber sections. *Tolerance* to accumulated dispersion scales like the inverse of the square of the symbol rate, and is about 1000 ps/nm for usual 10 Gb/s NRZ systems, which corresponds to about 60 km SMF fiber or 240 km LEAF fiber. At 100 Gb/s, tolerance would fall to 10 ps/nm (600 m SMF). Hence dispersion compensation is required, and is generally achieved with specific fiber sections called DCFs (Dispersion Compensating Fibers) exhibiting an opposite dispersion sign to the one of transmission fiber sections (also referred to as fiber spans) in the propagation waveband, so that the accumulated dispersion remains close to zero, thus enabling to minimize signal distortions. Those DCFs have typical dispersions of $[-100; -250]$ ps/(nm/km) at 1550 nm and are located regularly along the link, within the inline amplifiers, as illustrated in Fig. 2: the optical pulses carrying the digital information tend to broaden but the succession of fibers with different dispersion signs limits the broadening, and then the resulting inter-symbol interference at the receiver side.

Since DCFs cannot compensate perfectly for the dispersion of a transmission fiber for every wavelength of the C-band at the same time, some accumulated dispersion remains uncompensated after transmission, and some adaptive, per channel, dispersion compensation might be required at receiver side, especially for symbol rates higher than 10 Gb/s. This is another reason why signal integrity cannot be fully recovered stems from optical non-linear effects.

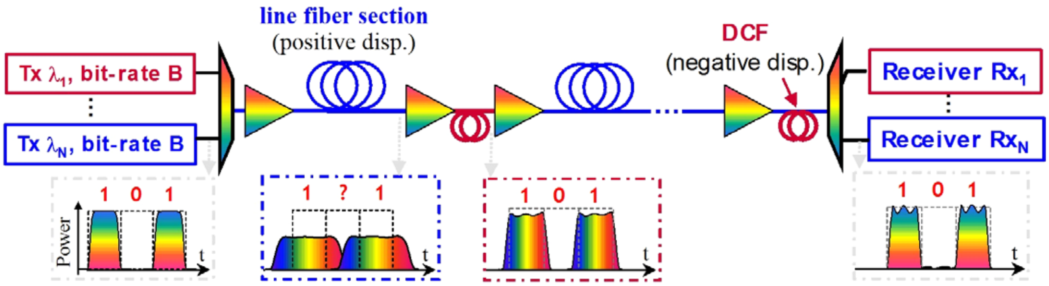

Fig. 2. WDM transmission link with line fiber sections and Dispersion Compensating Fibers (DCF).

2.6. Kerr non-linearities and dispersion-management

In the early days of lightwave systems, non-linear phenomena were only considered as secondary by system designers. The main concern was to manufacture flat-gain amplifiers with maximum output power, for the optical signal-to-noise ratio in all channels to remain above some allowed limit. As capacities and distances increased, it progressively became apparent that upper-power limits should not be trespassed either, as a result of stronger non-linear effects. Optimal system design thus requires that neither upper, nor lower power limits be approached or crossed during the entire operation life of the system.

Non-linear phenomena can be divided into two categories, those stemming from electronic non-linearities, namely the Kerr effect, and those stemming from atomic/molecular/material non-linearities, namely Stimulated Brillouin Scattering (SBS), core electrostriction, and inter-channel Self-Induced Stimulated Raman Scattering (SI-SRS). Unexpectedly, these effects occur at relatively low powers in the fiber (a few mWs or dBm), both because of the long integration distances (10–10000 km) and of the confinement of this power in a small region thus yielding high intensities ($\mathrm{kW/cm^2}$). This confinement is characterized by the effective area of the fiber, A_{eff}, which is fiber-type specific (80 μm^2 for SMF, 72 μm^2 for LEAF, 15–20 μm^2 for DCFs around 1550 nm).

We focus here on Kerr effect, which translates the dependence of the instantaneous fiber refractive index $n(z,t)$ on the signal intensity $I(z,t)$. The intensity is simply related to the instantaneous power profile $P(z,t)$ via $I(z,t) = P(z,t)/A_{\mathrm{eff}}$. The magnitude of this effect is determined by the non-linear coefficient n_2, according to the relation [4]:

$$n(z,t) = n_0 + n_2 \frac{P(z,t)}{A_{\mathrm{eff}}} \tag{4}$$

where n_0 is the linear part of the refractive index, while n_2 is expressed in $\mathrm{m^2/W}$. What actually determines the magnitude of fiber Kerr non-linearity (regardless of power) is more accurately determined by the ratio n_2/A_{eff}. While the parameter A_{eff} has become a common differentiating factor to qualify commercial fibers, the correct comparison between fiber types should only rely on the n_2/A_{eff} coefficient. Systematic experiments conducted so far have shown no large variation of n_2 with the type of fiber. The non-linear index ranges between $n_2 = 2.5 \times 10^{-20}$ and $3.0 \times 10^{-20}\ \mathrm{m^2/W}$.

In the propagation equation (3), the Kerr effect is accounted for by γ, the non-linear coefficient, with $\gamma = 2\pi n_2/\lambda A_{\mathrm{eff}}$.

Kerr non-linearities can be categorized into four types of physical phenomena:

- Self-Phase Modulation (SPM) whereby the signal phase of a given channel is modulated proportionally to its own power. At the receiver end, the photodiode is phase-insensitive, but GVD converts some of the phase modulation into intensity modulation, causing signal distortions;
- Cross-Phase Modulation (XPM), whereby the signal phase of a given channel is modulated proportionally to the power of the other channels, especially the close neighbors of this channel. Again, GVD converts some of the phase modulation into intensity modulation, causing signal distortions;
- Four-Wave Mixing (FWM), whereby the interaction between three WDM channels at three different wavelengths results into the generation of an intermodulation product at a fourth wavelength, which can fall on top of an existing fourth channel, producing detrimental crosstalk;

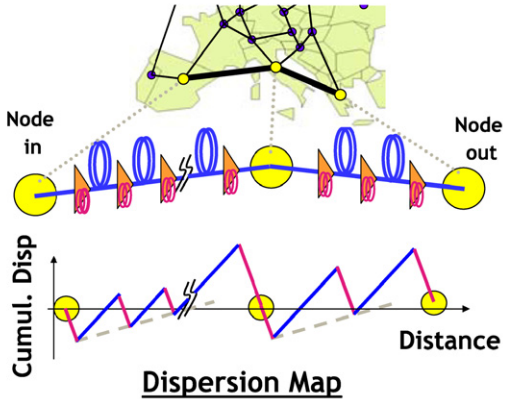

Fig. 3. Dispersion map of a transmission link between two distant optical nodes of a European optical network.

– Signal-noise non-linear interactions (referred to as Parametric-Gain or Modulation-Instability for intensity-modulated systems, non-linear phase noise for phase-modulated systems [4]), which strengthens or reduces the impact of amplifier noise, depending on the chromatic dispersion.

SPM is the straightforward, self-induced Kerr effect. After propagation along a length L of fiber with attenuation α, the phase of a channel with power $P(z,t)$ impaired by SPM can be simply derived from the propagation equation according to the well-known formula:

$$\Phi_{NL}(L,t) = \frac{2\pi}{\lambda}\int_0^L \frac{n_2(z)}{A_{\mathrm{eff}}(z)} P(z,t)\,dt \tag{5}$$

For typical WDM systems, the presence of amplifiers leads to the accumulation of SPM effects and phase shifts along the link.

SPM causes a broadening of the signal spectrum, since optical frequency shifts $\delta\omega = \partial\Phi_{NL}(L,t)/\partial t$ are generated on the pulse leading and trailing edges. Since this effect primarily concerns the signal phase, it does not affect intensity detection when chromatic dispersion is close to zero. In the case of non-zero chromatic dispersion, the interplay between SPM and chromatic dispersion results in a complicated phase-to-intensity conversion during signal propagation. Depending upon the chromatic dispersion sign, SPM is either beneficial, i.e. leading to pulse compression, or detrimental, i.e. leading to pulse broadening, distortion and irreversible breakup. The complex nature of the interplay between SPM and chromatic dispersion can also be intuitively understood since SPM generates phase modulation of the signal in the temporal domain, while chromatic dispersion meanwhile leads to phase modulation of the signal, but in the frequency domain, as it can be derived from the propagation equation (3).

Consequently, the outcome of the interaction between non-linear and dispersive effects strongly depends on the distribution of dispersion compensation and signal power along a transmission link. In presence of non-linearities, *Dispersion-Management* [9,14–16] consists in the clever distribution of dispersive elements along the link, so as to mitigate as much as possible non-linear and dispersive effects at the same time. Practically, it is characterized by a Dispersion Map, representing the evolution of the accumulated dispersion with distance, such as illustrated by Fig. 3.

It must be noted that, in order to minimize signal degradation, zero accumulated dispersion at the receiver is neither a sufficient solution (since dispersion management impact becomes critical) nor necessarily a good solution, since part of the accumulated dispersion has been practically compensated by non-linearities. The construction of a dispersion map usually follows simple rules, so as to deal with a limited number of degrees of freedom. In principle, any DCF with any cumulated dispersion can be inserted within an optical repeater before/after a section of transmission fiber. To make it simpler, periodic patterns are usually considered (Fig. 4).

The simplest class of dispersion map is referred to as *singly-periodic dispersion map* [16]: at transmission input, a pre-compensation DCF is used, then after each section of transmission fiber (also called span), some inline DCF is inserted at repeater site, so as to guarantee a constant accumulated dispersion from span to span (referred to as residual dispersion per span); at transmission end, some post-compensation DCF can be used before the receiver.

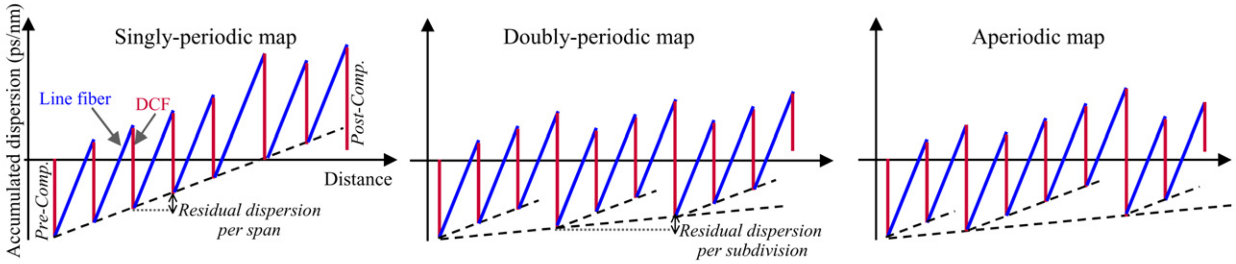

Fig. 4. Typical dispersion management schemes: singly-periodic (left), doubly-periodic (center), aperiodic (right) maps.

A second widespread class of dispersion map is called "*doubly-periodic dispersion map*" [17]. It can be seen as a concatenation of singly periodic maps of equal lengths (N spans), defined by the amount of pre-compensation, the residual dispersion per span, the residual dispersion per subdivision of N spans, and the final post-compensation at receiver side.

In deployed optical networks, singly periodic maps or *aperiodic maps* derived from the doubly-periodic concepts are widely used. The specificity of singly periodic maps is that total accumulated dispersion from the transmitter node to the receiver node depends on the transmission distance, possibly requiring dedicated post-compensation at receiver on a per channel basis. Aperiodic maps are derived from doubly periodic maps, with subdivisions of unequal lengths, corresponding to node spacing. Most of the time, the target residual dispersion from node to node is set to be equal or close to zero (similar to Fig. 3), so that the accumulated dispersion of any channel at any node will not depend on the light-path, and reception without dedicated post-compensation might be possible.

Dispersion management is widely used in long-haul terrestrial and submarine systems, in backbone optical networks, for single-channel as well as WDM applications, in order to mitigate also XPM and FWM impairments. In Section 4, we will show that even in the presence of dispersion management and especially for optimized dispersion maps, the accumulated non-linear phase shift induced by SPM, as defined by (5), remains a relevant parameter to quantify the impact of all non-linearities [6], proportional to the input power into the different amplified fiber sections, and to the number of fiber sections (assuming same input power from section to section). A simplified parameter is the product between number of sections and power [18], sometimes called "Integrated Power". Despite being defined primarily for SPM, non-linear phase shift or even integrated power still remain reliable parameters to quantify the amount of all non-linearities, even in presence of XPM, and FWM. A usual way to quantify system tolerance to non-linearities is to assess the so-called non-linear threshold, corresponding to the amount of non-linearities yielding a given penalty. When the symbol rate increases, SPM-induced impairments tend to increase, while the impact of XPM, FWM and signal-noise non-linear interaction tend to fade [9].

The impact of dispersion management compared to full dispersion compensation at terminals is far from negligible since it typically increases the tolerance to non-linearities by a factor of 10, which relaxes constraints on the maximal input power. Thus it enables to increase transmission reach significantly, by at least a factor of 3, as shown in Section 4. Dispersion-management has also replaced the former concepts of solitons [4], taking benefit of fibers with alternate signs of dispersion to improve robustness to intra-channel and inter-channel non-linear interactions while relaxing constraints on optical pulses powers and temporal widths.

2.7. *Other physical limitations*

Other phenomena impair system propagation, such as Polarization Mode Dispersion (PMD), crosstalk, filtering due to optical nodes, are described in more details in [19,20]. In the following, we focus on the interactions between the previously described effects.

3. Design tools to predict performance and design optical systems

Due to the complexity of optical transmissions systems and the number of interacting physical phenomena, design tools, based on numerical simulations, experiments and theoretical back-up, are essential to predict system performance accurately, and to guide the choices of components arrangements and settings for optimal performance. In

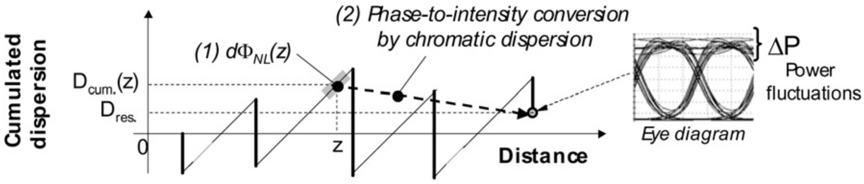

Fig. 5. Principle of Phase to Intensity Conversion, with SPM-induced phase shift at distance z, converted into intensity noise by chromatic dispersion from distance z to transmission end.

this section, we first present design tools to optimize dispersion management, i.e. to optimize the dispersion distribution along fiber links. Then, we present two common approaches to predict system performance, from synthetic parameters.

3.1. Dispersion management tools

Engineering rules can be used to optimize system features for best performance, such as to set dispersion management. Analytical tools to optimize dispersion management are generally based on either small-signal models [23,24] or linearization of the Non-Linear Schrödinger Equation ruling propagation along the whole system [25–27], and have generally been developed after identification of part of the rules from comprehensive campaigns of thousands of numerical simulations backed by a few validation experiments [28,29].

One of them is called Phase to Intensity Conversion criterion (PIC), and is an easy-to-handle-tool that enables one to get good physical intuitions on dispersion management at 10 and 40 Gb/s [16,23] – see Fig. 5. The PIC factor is in fact a simple estimation of the intensity noise at receiver end coming from the conversion of non-linear phase shifts (SPM/XPM) into intensity due to Group Velocity Dispersion (GVD) along the line. At a propagation distance z, the accumulated dispersion since the transmitter side is $D_{\mathrm{cum}}(z)$ and Kerr effect produces a non-linear phase shift at pulsation offset

$$\omega: \quad d\varphi_{NL} = -\frac{2\pi n_2}{\lambda A_{\mathrm{eff}}} P(z,\omega)\, dz,$$

assuming conventions in $(\omega t - kz)$; at the receiver side, the accumulated dispersion is D_{res}. In the small-signal approximation, we can expect partial conversion of the phase perturbation into intensity across the dispersive media from z to receiver characterized by its accumulated dispersion $D_{\mathrm{res}} - D_{\mathrm{cum}}(z)$, following:

$$dPIC(z,\omega) = \frac{dP(z,\omega)}{2\langle P\rangle} = \sin\left[\frac{\omega^2\lambda^2}{4\pi c}\big(D_{\mathrm{cum}}(z) - D_{\mathrm{res}}\big)\right] d\varphi_{NL}(z) \tag{6}$$

The contributions of all the spatial steps of the link can be added to get an integrated expression of the resulting intensity perturbation, including or not integration over frequency offsets, SPM, XPM, signal power spectral density, optical and electrical filters; dispersion management can thus be optimized such that the estimation of the integrated intensity perturbation is zeroed or set within a certain range close to zero. So far, the most simple and relevant way to use PIC criterion has been found to consider that the relevant frequencies in the calculation of the intensity perturbation estimate are small enough, enabling to approximate the sine function in Eq. (6) to identity, and then to integrate this equation over the spatial dimension; this finally leads to this simple relationship linking dispersion map parameters, when aiming at zeroing the overall estimation of the induced intensity perturbation.

$$PIC(\omega) = \int dPIC(z) \approx \frac{\omega^2\lambda^2}{4\pi c^2} \sum_{\mathrm{span}\,k} \phi_{nl,k}\left(\frac{D_{\mathrm{loc}}^{(k)}}{\alpha} + \big(D_{\mathrm{cum,input}}^{(k)} - D_{\mathrm{res}}\big)\right) = 0 \tag{7}$$

with, for each fiber (k), the local dispersion D_{loc}, the attenuation α and the cumulated dispersion at span input $D_{\mathrm{cum,input}}$, and the non-linear cumulated phase over the span ϕ_{nl}.

Excellent agreement has been found between the predictions of such a formula and numerical/experimental results [16,23], especially at 40 Gb/s and higher bit-rates, as illustrated by Fig. 6.

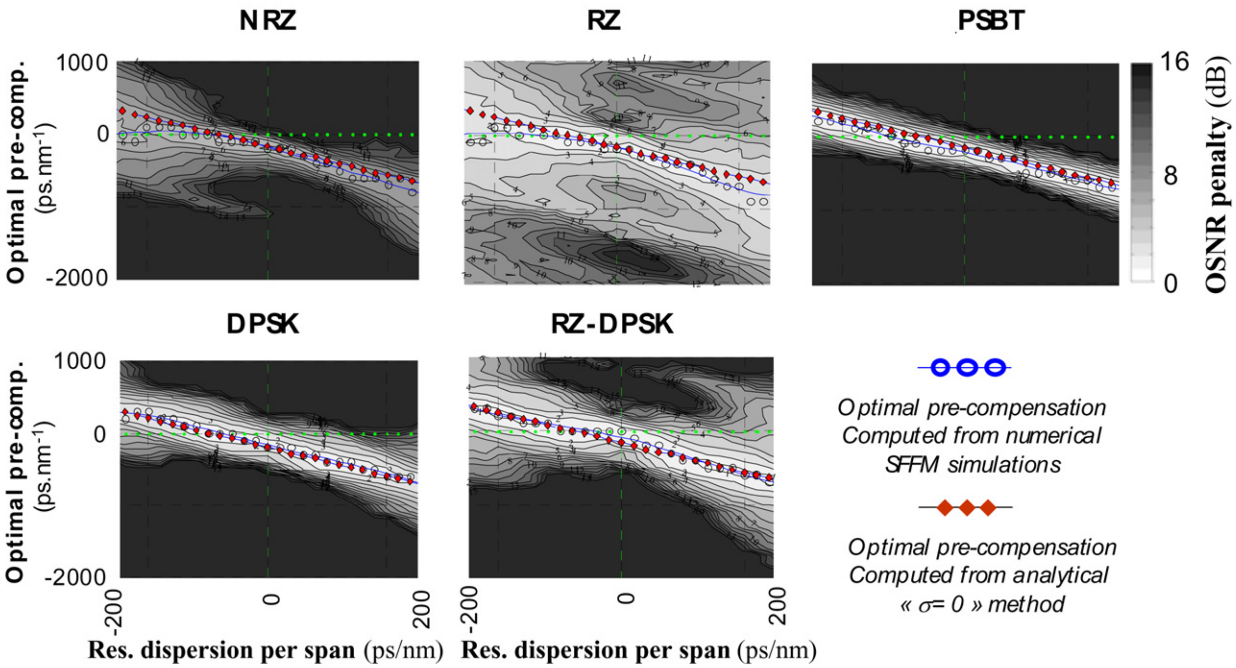

Fig. 6. Contour plots of OSNR penalty as a function of dispersion management parameters such as pre-compensation and residual dispersion per span for a single-channel 40 Gb/s transmission over 5 × 100 km SMF fiber, using a singly-periodic dispersion map, for various modulation formats. Red plots correspond to PIC predictions, blue circles to optimal values of pre-compensation for each value of inline residual dispersion.

It is therefore very convenient to simplify the optimization of dispersion management, all the more as very simple expressions can be extracted to the usual cases of singly- or doubly-periodic maps, such as:

$$PIC \propto \phi_{nl,\mathrm{tot}}\left(Pre - D_{\mathrm{res}} + \frac{N_{\mathrm{spans\ per\ subdiv}} - 1}{2} D_{\mathrm{res,span}} + \frac{Nb_{\mathrm{subdiv}} - 1}{2} D_{\mathrm{res,subdiv}} + \frac{D}{\alpha}\right) = 0 \tag{8}$$

Here, we consider a doubly-periodic dispersion map such as in Fig. 4, with Nb_{subdiv} subdivisions (or node sections) of $N_{\mathrm{spans\ per\ subdiv}}$ spans each, and negligible non-linearities stemming from DCFs. ϕ_{nl} refers to the total cumulated non-linear phase, D to local chromatic dispersion of line fiber spans, Pre to the cumulated dispersion of the pre-compensation module at the transmitter side, $D_{\mathrm{res,span}}$ to the residual dispersion per span, including the accumulated dispersion over one line fiber span and the following inline DCF after each span but the last one of a subdivision, and $D_{\mathrm{res,subdiv}}$ refers to the cumulated dispersion per subdivision.

Some more advanced models, based on linearization of the Dispersion-Managed Non-Linear Schrödinger Equation, are still under investigation, to predict system degradation and enable dispersion map optimization, and very similar expressions can be obtained, unfortunately out of their strict mathematical domain of validity. They indeed assume very few non-linearities on the whole link, and their use must therefore be considered cautiously and systematically validated by numerical or experimental simulations, otherwise possibly leading to erroneous prediction tools [26,27]. The establishment of relevant design rules is therefore the result of patient interactions between analytical models, experiments and simulations.

3.2. Performance prediction

Predicting the performance of a system requires that one:

- models and characterizes the couple transmitter/receiver and its tolerance to basic linear effects such as OSNR, PMD, accumulated chromatic dispersion, to filtering;
- identifies the key parameters describing the transmission system, and to make a distinction between rather extensive, cumulative parameters (such as OSNR degradation, PMD accumulation, accumulation of non-linearities,

accumulated dispersion, ...) and rather intensive features corresponding to system constraints such as line fiber types, lengths, channel bit-rate, channel spacing, local chromatic dispersion and power distribution, ... ;
– models signal degradation under the identified constraints, as a function of the identified cumulative parameters, as synthetic as possible, based on analytical or empirical engineering rules.

Accurate performance prediction is essential for system dimensioning, in order to build high-performance transmission WDM systems while minimizing the required number of optoelectronic regenerators (since multi-channel amplification brings far less complexity than a multiplication of per-channel regenerators) and costs. Accurate and simple prediction tools are also crucial for dynamic transparent networks for the possibly dynamic assignment of new light-paths over operational networks [19].

Two models are generally considered to predict BER (or rather Q factor): a first model [21], denoted as model 1, aims to calculate the analytic expression of Q, based on perturbations of Eq. (2), and a second model [19], denoted as model 2, based on the addition of penalties stemming from the different physical effects.

In model 1 [21], the Q factor expression is calculated after separation between deterministic signal degradations (through the estimation of an eye opening penalty as a function of Dispersion, SPM, and one condition of Differential Group Delay, i.e. an instantaneous realization of PMD), and noise-like perturbations, including ASE noise, but also models for XPM/GVD-induced phase and intensity noises, FWM-induced noise, crosstalk, ... Deterministic impairments lead to an estimation of the difference between mean intensities from marks or spaces in Eq. (2), while noise-like processes impact the calculation of standard deviations of marks and spaces, enabling to calculate a Q factor. PMD impact can be accounted for by the estimation of the mean PMD value of the link, as well as the assumption of Maxwellian distribution for possible instantaneous PMD values. This way, it is possible to weight Q factor by the distribution of possible PMD instantaneous values to obtain the outage probability (probability that Q factor is lower than a reference value Q_{ref}). The transmission link will therefore be considered as feasible, provided the Q factor is higher than Q_{ref} and the outage probability lower than a reference value such as 10^{-5}, i.e. Q higher than Q_{ref} with a probability of $(1–10^{-5})$.

$$Q = \frac{``\mu_1 - \mu_0"(\bar{P}, \Phi_{nl}, D_{\text{cum}}, \text{DGD}, \ldots)}{``\sigma_1 + \sigma_0"(\bar{P}, \text{OSNR}, \text{XPM}, \text{FWM})} \quad \Rightarrow \quad \text{Outage probability} = \int_0^{Q_{\text{ref}}} pdf(Q)\, dQ \tag{9}$$

In Eq. (9), "$\mu_1 - \mu_0$" is the relative power of marks versus spaces at sampling time, that depends on the average signal power $\bar{P}$, the non-linear phase shift ϕ_{nl}, the accumulated (or residual) dispersion over the link D_{res}, and the Differential Group Delay DGD (i.e. PMD instantaneous value); σ_1 and σ_0 respectively correspond to the standard deviations of signal power for marks and spaces at sampling time, include Amplified Spontaneous Emission-related contributions, estimates of the intensity noise regarding XPM and FWM, and depend on the signal power distribution of each channel, optical signal to noise ratio OSNR ... From the calculation of Q factor for each value of DGD, and from the known distribution of DGD, one obtains the power density function (pdf) of Q factor, thus allowing to derive the outage probability that Q is lower than Q_{ref}.

Model 2, described in more detail in this issue of the *Comptes-Rendus de Physique* [19], is not based on the analytical expression of Q factor since its connection with BER assumes Gaussian distributions of the received intensities at receiver side. Model 2 is rather based on the separation between actual OSNR and required OSNR for a reference Q factor Q_{ref}, as proposed in Section 2.4:

$$\begin{aligned} &Q(\Phi_{nl}, D_{\text{res}}, \text{OSNR}, \text{PMD}, \text{XTalk}, \ldots) \\ &\quad = Q_{\text{ref}} + \zeta(\Phi_{nl}, D_{\text{res}})\big(\text{OSNR} - \text{OSNR}_{\text{req}}^{Q_{\text{ref}}}(\Phi_{nl}, D_{\text{res}}, \text{PMD}, \text{XTalk}, \ldots)\big) \end{aligned} \tag{10}$$

Here, the assessment of lightpath feasibility thus corresponds to estimating whether the actual OSNR is higher than the required OSNR corresponding to modulation limitations and system impairments. Particularly, $\text{OSNR}_{\text{req}}^{Q_{\text{ref}}}$ corresponds to the required OSNR after transmission, to guarantee a Q factor equal to Q_{ref}, and depends on non-linear phase, residual dispersion, PMD and crosstalk terms. The function $\zeta(\Phi_{nl}, D_{\text{res}})$ is related to the observation that Q factor (in dB) generally scales proportionally with OSNR (in dB) with a slope ζ, lower to 1 in usual conditions of OSNR, due to pattern effects [19,22].

Eq. (10) can be rewritten in terms of OSNR penalties:

$$Q(\Phi_{nl}, D_{\text{res}}, \text{OSNR}, \text{PMD}, \text{XTalk}, \ldots) = Q_{\text{ref}} + \zeta(\Phi_{nl}, D_{\text{res}})\left(\text{OSNR} - \text{OSNR}_{\text{req,btb}}^{Q_{\text{ref}}} - \text{Pen}^{Q_{\text{ref}}}(\Phi_{nl}, D_{\text{res}}, \text{PMD}, \text{XTalk}, \ldots)\right) \tag{11}$$

with $\text{Pen}^{Q_{\text{ref}}}(\ldots)$ being the OSNR penalty after propagation, for reference Q factor Q_{ref}, equal to the difference in the required OSNR for reference Q_{ref}, after propagation ($\text{OSNR}_{\text{req}}^{Q_{\text{ref}}}$) and without propagation $\text{OSNR}_{\text{req,btb}}^{Q_{\text{ref}}}$.

Eventually, assuming that the joint induced penalty due to the different sources of degradation is equal to the sum of the induced penalties of each source [19], we get:

$$Q(\Phi_{nl}, D_{\text{res}}, \text{OSNR}, \text{PMD}, \text{XTalk}, \ldots) = Q_{\text{ref}} + \zeta(\Phi_{nl}, D_{\text{res}})\left(\text{OSNR} - \text{OSNR}_{\text{req,btb}}^{Q_{\text{ref}}} - \text{Pen}^{Q_{\text{ref}}}(\Phi_{nl}, D_{\text{res}}) - \text{Pen}^{Q_{\text{ref}}}(\text{PMD}) - \text{Pen}^{Q_{\text{ref}}}(\text{XTalk})\right) \tag{12}$$

This assumption enables to separately characterize the impact of the different phenomena, and get an overall estimation of system performance. It must be noted that the non-linear and dispersive terms cannot be treated separately, due to their strong interplay.

The model can be refined by dealing differently with deterministic and time-varying or statistical effects (due to PMD, or partial knowledge of some system features for instance). A possible simplification of model 2 consists in estimating a tolerable amount of penalty for each physical effect, thus a maximum amount of the quantifier for this effect and an overall tolerated penalty, or minimum required OSNR; feasibility assessment consists in checking that the limit is not crossed for each effect, and that the actual OSNR is higher than the minimum required OSNR.

For both models, a performance estimator can be built based on analytical considerations and measurements stemming from experiments or numerical simulations, such as evolution of the eye opening or penalty with non-linearities, for a pre-defined dispersion management scheme, evolution with PMD, crosstalk, accumulated dispersion....

4. Assessing the impact of accumulated non-linearities, from homogeneous to heterogeneous systems

4.1. Predicting the resistance to non-linearities for dispersion-managed systems with one line fiber type

In the absence of chromatic dispersion, the sole impact of Kerr effect is a time-varying phase shift given by (5) on the propagating optical field, proportional to signal power at each time. In a multi-channel environment, it causes detrimental FWM between the channels, enhanced by perfect phase matching. Propagation on fibers with very low values of chromatic dispersion is therefore best avoided, and most transmission systems are dispersion-managed and involve non-zero dispersion fibers, with alternate signs of dispersion. Due to the complex Kerr/dispersion interaction, finding a relevant parameter accounting for the accumulation of non-linearities, and directly linked to the impact on the system, is not straightforward for dispersion-managed systems.

To demonstrate this in [6], we considered a singly-periodic terrestrial $N \times 40$ Gbit/s system affected not only by Self-Phase Modulation but also by Cross-Phase Modulation and Four-Wave Mixing. As discussed above, the impact of these effects can be mitigated through optimized dispersion management along the transmission link, but up to certain point only. Further reduction of their impact would require a reduction of the power per channel launched into the line, which faces the stumbling block of the minimal signal-to-noise requirement at the receiver end. Thus, it is an optimal balance between non-linear effect and noise accumulations which determines the achievable haul of a system. To rate non-linear effect accumulation, simple criterions such as the span number of a link, or the input power into the line fiber [30,31] have first been investigated. We describe here two synthetic tools: firstly the product $M \times P_{\text{line}}$ [18] between number of spans M and input power into line fiber P_{line}, and secondly, the non-linear phase which has the additional advantage of taking into account the impact of non-linearities in the dispersion-compensating fiber as well as in the line fiber [6].

As we focus on the ultimate impact of non-linear impairments, noise limitations are overlooked and dispersion management is assumed optimized in this subsection. To assess the accuracy of the non-linear phase as performance estimator, we investigate next the correlation between this estimator and a more conventional one obtained through numerical simulations, the OSNR penalty for 10^{-5} BER. Here, we always consider an average penalty over the five central channels of a nine-channel multiplex, after full optimization of the dispersion map.

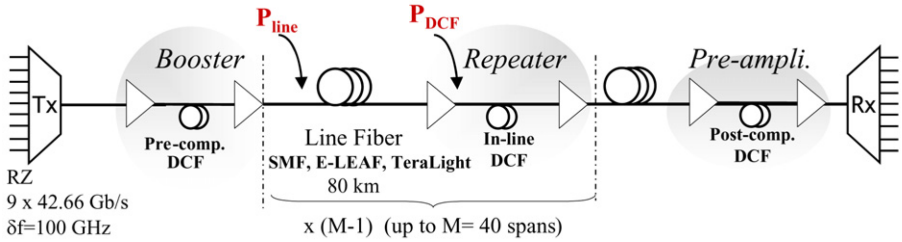

Fig. 7. Simulated set-up for assessment of impact of non-linearities.

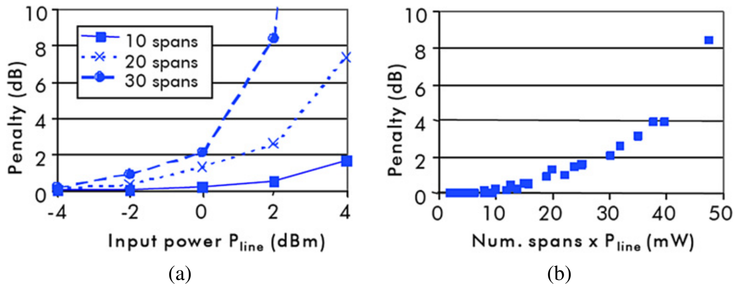

Fig. 8. (a) Penalty vs. input power P_{line} into line fiber after $M = 10$, 20 or 30 spans; (b) Penalty vs. $M \times P_{\text{line}}$ for variable powers and distances (from 5 to 35 spans).

The system under study is depicted in Fig. 7. It is a WDM 9×42.66 Gbit/s dispersion-managed, terrestrial, ultra-long haul link, based on return-to-zero (RZ) modulation. The transmitter consists of nine channels spaced 100 GHz apart, centered around 1550 nm, with the same polarization. Each channel is modulated by a 128-bit long sequence, decorrelated with that of the other channels by introducing a random delay. The basic transmission link consists of up to 40 sections of 80 km-long line fiber (Standard Single Mode Fiber (SMF), TeraLight$^{\text{TM}}$, or LEAF$^{\text{TM}}$ [6], essentially characterized by their chromatic dispersion at 1550 nm, of 17, 8, and 4.25 ps/(nm/km) respectively) with discrete, dual-stage erbium-based repeaters. Chromatic dispersion is compensated for within each amplifier following a singly-periodic scheme at the link input (pre-compensation), along the link (in-line compensation) and at the link output (post-compensation) by sections of Dispersion Compensating Fiber (DCF). In addition, the dispersion slope of DCF modules is assumed to fully compensate for that of the line fiber. To investigate the performance of such a system, we varied all the parameters of the dispersion maps for any transmission distance or input powers. The cumulated dispersion of the pre-compensation module was varied between 0 and −720 ps/nm (40 ps/nm step) for SMF, and between 0 to −300 ps/nm (20 ps/nm step) for TeraLight and LEAF. Post-compensation was optimized for every channel at the end of the link. In-line compensation was not varied from one simulation to another. It was set to fully compensate for the cumulative dispersion of one transmission fiber span (100% in-line compensation), but on average only. The actual value was randomly picked with [90%, 110%] according to a uniform distribution, in order to emulate installation constraints.

First, we investigate the dependence of the penalty on the transmission distance and the input power P_{line} into one type of line fiber (SMF), assuming that the input power into the DCF P_{DCF} is proportional to P_{line}, but 8 dB lower. The curves of Fig. 8(a) show the optimum OSNR penalty results as a function of P_{line} for different transmission distances ($M \times 80$ km, M being 10, 20 or 30). P_{line} is varied within [−4 dBm; +4 dBm] by 2 dB step. At each point, only the penalty corresponding to optimal dispersion map is shown. Not surprisingly [16,15], the penalty is found to increase with both parameters M and P_{line}, in an exponential-like manner. If we now express it as a function of the number of spans times power $M \times P_{\text{line}}$ product, the former set of curves (for different transmission distances) can be summarized in a single one (Fig. 8(b)), which means that the penalty depends bi-univocally on the $M \times P_{\text{line}}$ product, provided dispersion management is optimized. A natural extension of this synthetic parameter to the case of fiber input powers P_{line} different from fiber section to another, is the sum of those input powers along the transmission link, that can be referred to as integrated power $IP = \sum_{\text{line fiber } k} P_{\text{line}}^{(k)}$.

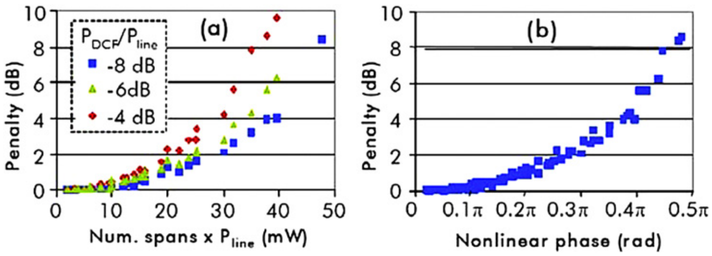

Fig. 9. (a) Impact of non-linearity in the DCF: penalty vs. $M \times P_{\text{line}}$, with P_{DCF} 4, 6 or 8 dB lower than P_{line}; (b) Dependence of penalty on non-linear cumulated phase.

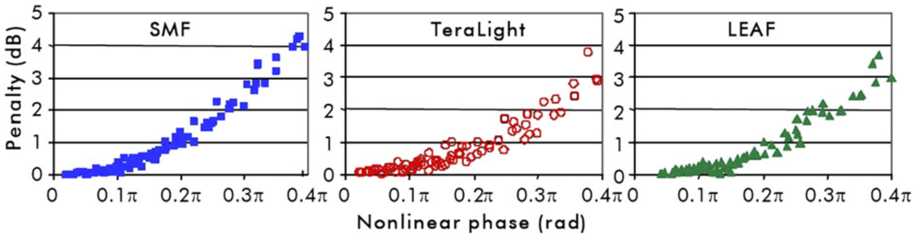

Fig. 10. Assessment of non-linear phase as performance estimator: impact of line fiber type.

Secondly, we investigate the dependence of the penalty on the $M \times P_{\text{line}}$ product (still over SMF), assuming that the amount of non-linear effects in the DCF is increased, which is obtained by changing the ratio between P_{DCF} and P_{line} from 8 dB to 6 and 4 dB, as depicted in Fig. 9(a). The penalty is found to increase with the power into the DCF, which indicates that the product $M \times P_{\text{line}}$ does not fully assess the non-linear limitations of the system. Obviously, the line fiber and the DCF are two types of fibers that differ in terms of effective area A_{eff} and non-linear index n_2. Their respective contributions should therefore be weighted by the non-linear strength n_2/A_{eff} of the involved fiber types, which suggests using the non-linear phase shift Φ_{NL} as a more accurate criterion for performance assessment. Φ_{NL} is defined after Eq. (5).

By overlooking its time-dependence and keeping only the mean contributions, we obtain the following formula:

$$\Phi_{NL} = \frac{2\pi}{\lambda} \int\limits_{\text{link}} \left(\frac{n_2 P}{A_{\text{eff}}} \right)(z)\, dz = \frac{2\pi}{\lambda} M \left(\frac{n_2 P L_{\text{eff}}}{A_{\text{eff}}} \bigg|_{\substack{\text{line} \\ \text{fiber}}} + \frac{n_2 P L_{\text{eff}}}{A_{\text{eff}}} \bigg|_{\text{DCF}} \right) \tag{13}$$

λ being the current wavelength, P the input power into the considered fiber sections, and L_{eff} the effective length [6]. Fig. 9(b) shows the penalties of Fig. 9(a) as a function of the non-linear phase. It can be seen that there is a very good correlation between the simple concept of non-linear phase and the concept of penalty, as the relationship between them appears as almost bi-univocal. In particular, the non-linear phase rates fairly well the impact of FWM and XPM, even though these effects do not appear explicitly in Φ_{NL}. Naturally, the relationship between Φ_{NL} and the penalty depends on the chromatic dispersion of the fiber, the bit-rate, the modulation format and the channel spacing, and therefore should be re-estimated any time one of these parameters is changed. As an example, Fig. 10 shows the penalty versus the non-linear phase computed over SMF, TeraLight or LEAF fibers.

Further simulations confirmed that the penalty depends straightforwardly with the effective areas and with the span length (independent on it, provided that it is significantly larger than L_{eff}), in good accordance with the non-linear phase. Besides, ϕ_{NL} was also found applicable to Raman-based systems, provided the non-linear phase is integrated using the actual power profile along the line in Eq. (13). In all cases, the penalty followed the curves of Fig. 7.

In summary, we have shown through extensive numerical simulations, that the cumulated non-linear phase is a simple but accurate parameter to assess the performance of $N \times 40$ Gbit/s terrestrial systems. This parameter can be of high interest for constraint-based routing algorithms in ultra-long haul transparent networks, or simply to design a system. Indeed, at each node (or span), the knowledge of the non-linear phase and OSNR evolution should help to decide whether a path should be regenerated or not. However, the ability of the non-linear phase to actually predict system performance is conditioned by one stringent requirement, namely that the dispersion map is optimized. In [7] and [8], the non-linear phase criterion was further validated for singly- and doubly-periodic dispersion maps, at 10 and 40 Gb/s channel bit-rates, while experimental evidence is referred to in [19]. This concept of non-linear phase for dispersion-managed systems can also be deduced from theoretical analyses, such as small-signal models [23] or models based on the linearization of the Dispersion-Managed NLSE [25], assuming that the product between total accumulated inline dispersion in physical notations [4] and the square of the bit-rate remains sufficiently low with respect to 1.

4.2. Application

Being able to quantify how non-linearities accumulate in a dispersion-managed transmission link, scaling with integrated power or more precisely with accumulated non-linear phase, is decisive to simply design systems and predict transmission reach. Indeed, we can derive from a few measurements on a generic system the evolution of penalty (or equivalently OSNR requirements for the system to be operated) with power distribution and distance for a wide class of systems, and combine this information with actual OSNR evolution. We first define the concept of non-linear threshold to quantify tolerance to non-linearities, and derive simple expressions of the transmission reach and optimum power setting, assuming here transmission systems mainly impaired by noise and non-linear/chromatic dispersion limitations.

4.2.1. Determination of a non-linear threshold

Let us consider a class of transmission systems characterized by given bit-rate, modulation format, and channel spacing, and operated over one type of line fiber with suitable strategy of dispersion-management, such that the relationship between transmission penalty and non-linear phase becomes bi-univocal. For such systems, the tolerance to non-linearities is assessed thanks to the so-called *non-linear threshold* (NLT), i.e. the value of non-linear phases or integrated powers leading to a reference OSNR penalty, generally between 1 and 3 dB for a reference BER.

The chosen value of the reference penalty can be arbitrary or based on the minimization of BER with power at maximum transmission reach such as to achieve the reference BER. To get more insight on this, let us assume the generic relation between Q factor, OSNR and transmission penalties from Eq. (12) in Section 3.2. For simplicity, let us first assume identical line fiber sections, with the same power P_{line} at each line fiber span input, identical DCFs with the same input power, proportional to P_{line}, and eventually amplifiers with constant noise figures. As a result, OSNR and ϕ_{NL} are proportional to P_{line} in linear scale, or equivalently derivatives of OSNR^{dB} and $\phi_{NL,\text{dB}}$ with respect to $P_{\text{line,dB}}$ in (dB × dB) scale are equal to 1. At maximum transmission reach, to get a Q factor equal to Q_{ref} with optimized power P_{line}, the derivative of Q factor (in dB scale) with $P_{\text{line,dB}}$ is expected to be zero, such that we get from Eq. (12):

$$\underbrace{\frac{\partial Q_{\text{dB}}^2(\ldots)}{\partial P_{\text{dB}}}}_{0} = \frac{\partial \zeta(\ldots)}{\partial P_{\text{dB}}} \underbrace{(\text{OSNR}_{\text{dB}} - \text{Pen}_{NL,\text{dB}}(\Phi_{NL,\text{dB}}, D_{\text{res}}) - \ldots)}_{0 \text{ since } Q=Q_{\text{ref}}} + \zeta(\ldots) \cdot \left(1 - \frac{\partial \text{Pen}_{NL,\text{dB}}(\Phi_{NL,\text{dB}})}{\partial \Phi_{NL,\text{dB}}}\right) \tag{14}$$

Therefore, this optimum power indeed corresponds to an optimum value of non-linear phase such that the derivative of the penalty vs. non-linear phase function $\text{Pen}_{NL,\text{dB}}(\Phi_{NL,\text{dB}}, \ldots)$ (in dB × dB scale) is equal to unity. To this non-linear threshold corresponds a specific amount of penalty. The same reasoning also applies with use of the integrated power concept instead of the non-linear phase concept, since here, the integrated power is simply proportional to ϕ_{NL}.

Those concepts are illustrated by Fig. 11, which shows the evolution of the Q factor, the OSNR to get $Q = Q_{\text{ref}}$, and the actual OSNR as functions of input power into line fiber spans for a transmission system with length lower than (cf. Fig. 11(a)) or equal to (cf. Fig. 11(b)) the maximum reach such that $Q = Q_{\text{ref}}$ for optimal power. When the distance is lower than the system reach, the Q factor is higher than Q_{ref} over a finite range of powers allowing system operation; within this range of powers, the actual OSNR is higher than the required OSNR to get Q_{ref}. When distance increases, the actual OSNR curve is shifted down, since it decreases with distance, and the required OSNR curve is shifted to the left, towards lower values of power, since it actually depends on the product between power and number of line fiber spans. As a result, at maximum reach, the actual OSNR and required OSNR are tangent, corresponding to one single value of power for system operation, with Q factor equal to Q_{ref}. Thus, for this optimal power value, the derivative of the required OSNR to get Q_{ref} vs. power is equal to unity in (dB × dB) scale, meaning that a small increase in power would leads to an increase of OSNR exactly compensated by the increase of transmission penalty.

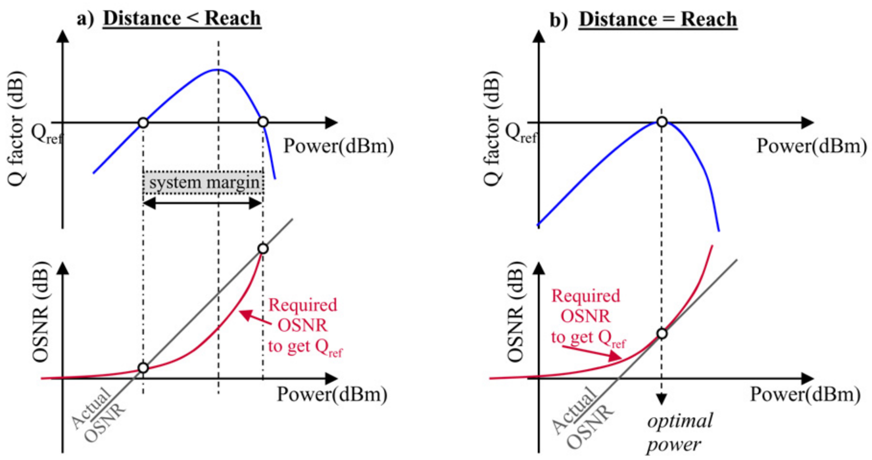

Fig. 11. Optimal power at maximum system reach. Evolution of Q factor (top) and actual OSNR/required OSNR to get $Q = Q_{\text{ref}}$ (bottom) as a function of input power into line fiber spans, for two configurations: distance lower than system reach, and distance equal to system reach (i.e. $Q = Q_{\text{ref}}$ for optimized power).

Since the required OSNR actually depends on the product between span number and power, or more generally on the non-linear phase shift, this optimum power indeed corresponds to an optimum value of the non-linear phase (or integrated power) such that the derivative of the required OSNR with respect to the power is equal to 1 dB/dB. Eventually, as abovementioned, since the non-linear phase (or integrated power) is proportional to power (in linear scale) and since required OSNR (in dB scale) is equal to the OSNR penalty plus a constant term, then this optimum value of the non-linear phase (resp. integrated power) is such that the derivative of the OSNR penalty with respect to the non-linear phase (resp. integrated power) is equal to unity in (dB × dB) scale.

It is then possible to characterize a whole class of systems by the knowledge of the non-linear threshold NLT and the corresponding transmission penalty, paving the way to simple reach estimation and power tuning.

4.2.2. Transmission reach and power setting of an homogeneous system

Let us consider here a class of systems characterized by their non-linear threshold NLT, corresponding to a reference penalty, thus to a required OSNR after transmission, denoted S, to obtain a reference BER. We will consider a transmission system belonging to this class, with M identical line fiber sections, and identical repeaters within line fiber sections (with constant, identical noise figures, identical output per channel power P_{line} and hosting Dispersion Management modules). To account for the accumulation of non-linearities, we can consider equivalently either the non-linear phase, or the integrated power, simply proportional. In the following, we choose the non-linear phase terminology, ϕ_{NL}. With these assumptions, the OSNR and ϕ_{NL} evolutions with M and P_{line}, as well as system limitations, can be expressed as follows:

$$\begin{cases} \text{OSNR}(P_{\text{line}}, M) = \text{OSNR}^\circ(P^\circ, M = 1) \cdot \frac{P_{\text{line}}}{P^\circ \cdot M} \geqslant S \\ \Phi_{NL}(P_{\text{line}}, M) = \Phi^\circ_{NL}(P^\circ, M = 1) \cdot \frac{P_{\text{line}}}{P^\circ} \cdot M \leqslant \text{NLT} \end{cases} \tag{15}$$

with P° as an arbitrary reference power, OSNR$^\circ$ (resp. ϕ°) as the OSNR (resp. the accumulated non-linear phase) after one section of line fiber and the following inline repeater, for input power P°, assuming infinite OSNR and null non-linear phase at section entry. The sets of Eqs. (15) mean that the OSNR, which scales proportionally with P_{line} and with the inverse of span number, is expected to remain above the required OSNR limitation S at non-linear threshold, while at the same time, the non-linear phase, which scales proportionally with P_{line} and span number, is expected to remain below the non-linear threshold NLT, as illustrated by Fig. 12.

At maximum reach $M_{\max}$, with optimized power P_{opt}, non-linear phase will be equal to NLT, and the OSNR will be equal to the corresponding required OSNR S. Thus, we get:

$$\begin{cases} M_{\max} = \sqrt{\frac{\text{NLT}}{S}}\sqrt{\frac{\text{SNR}^\circ}{\Phi^\circ}} \\ P_{\text{line,opt}} = P^\circ \cdot \sqrt{\frac{\text{NLT}\cdot S}{\Phi^\circ \cdot \text{SNR}^\circ}} \end{cases}, \quad \text{or in dB scale} \quad \begin{cases} M_{\max,\text{dB}} = \frac{\text{NLT}_{\text{dB}} - S_{\text{dB}}}{2} + \frac{\text{SNR}^\circ_{\text{dB}} - \Phi^\circ_{\text{dB}}}{2} \\ P_{\text{line,opt,dBm}} = \frac{\text{NLT}_{\text{dB}} + S_{\text{dB}}}{2} - \frac{\Phi^\circ_{\text{dB}} + \text{SNR}^\circ_{\text{dB}}}{2} \end{cases} \tag{16}$$

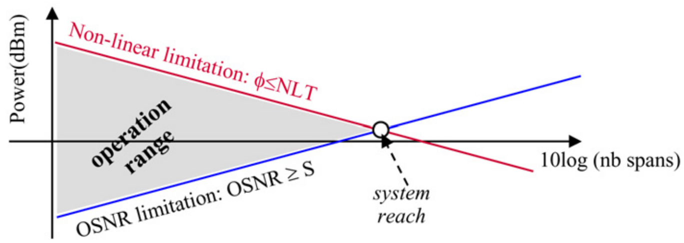

Fig. 12. Evolution of range of span input powers for system operation with respect to distance.

We clearly see the trade-offs between non-linearities and OSNR to determine the transmission distance. Up-to-now, replacing the non-linear phase concept by the integrated power is possible, leading to ad hoc rules. Such rules are very useful to compare the performance of modulation formats, to compare and optimize amplifier schemes including Erbium and/or Raman amplification [32,33], or to find trade-offs in the design of new line fibers or dispersion-compensating fibers [34].

Such tools can be extended to deal with fiber heterogeneity: the integrated power tool allows one to optimally set line-fiber input powers and predict reaches in the case of line fiber sections with different losses, while non-linear phase concept can further be applied to the heterogeneity between line fiber and DCF, as explained in Appendix A. Indeed, it appears that the optimum power combination for all fiber section, is to set the input power into each fiber section (characterized by ϕ° and OSNR°, and also by the NLT and S, here equal for all fiber sections) according to Eq. (16). To determine the system reach, one must check that:

$$\sum_{\substack{\text{fiber}\\ \text{section } k}} \frac{1}{M_{\max}^{(k)}} \leqslant 1 \tag{17}$$

In the case of identical sections of line fiber and DCF, the maximum achievable number of line fiber spans M is [35]:

$$\frac{1}{M} = \frac{1}{M_{\max}^{(\text{line fiber})}} + \frac{1}{M_{\max}^{(\text{DCF})}} \tag{18}$$

5. Predicting resistance to non-linearities for dispersion-managed systems with mixed line fiber types

The recent introduction of transparency, as well as the necessity to re-use legacy fiber as much as possible, brings new challenges in the efficient design of meshed optical networks, for instance coping with line fiber type heterogeneity. Indeed, it has now become almost common to deal with light-paths between two points of the network involving at least two different line fiber types [7,8,36–40], and it has therefore become crucial to use simple tools in order to predict accurately light-path feasibility. One of the most critical issues is to determine the tolerance to Kerr-like non-linear impairments, without requiring customized simulations or experiments for each possible configuration. We proposed in [7,8] a simple parameter, the weighted non-linear criterion, to predict the tolerance to non-linearities of an heterogeneous system composed of the concatenation of two homogeneous subsystems (each of which involving only one fiber type) from the sum of the non-linear contributions of both homogeneous subsystems, weighted by their own tolerance to non-linearities. Its potential was illustrated in an NRZ system at 10 Gb/s consisting of G.652 Standard Single-Mode fiber (SMF) and G.655 Large Effective Area Fiber (LEAF), assuming singly-periodic dispersion mapping for each subsystem. In [8], we reported on an extensive investigation of the accuracy of this criterion at both 10 and 40 Gb/s, with various modulation formats (NRZ, Phase-Shaped-Binary Transmission PSBT, Differential Phase-shift Keying DPSK [9]), over numerous system configurations using doubly periodic dispersion management schemes, typical of meshed networks. All these systems involved a combination of SMF and LEAF line fibers, since these fiber types are the most widespread and lead to very different propagation behaviors due to their different dispersions characteristics. In the following, we will illustrate this concept with NRZ format at 40 Gb/s.

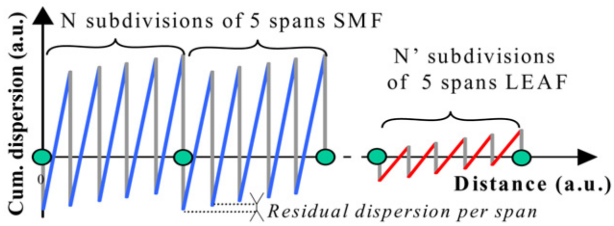

Fig. 13. Typical dispersion map of mixed system composed of SMF, then LEAF subsystems, each w/doubly periodic map ($N = 2$ subdivisions of 5 spans SMF, then N' subdivisions of 5 spans LEAF, with null residual disp. per subdivision, and 50 ps/nm residual disp. per span).

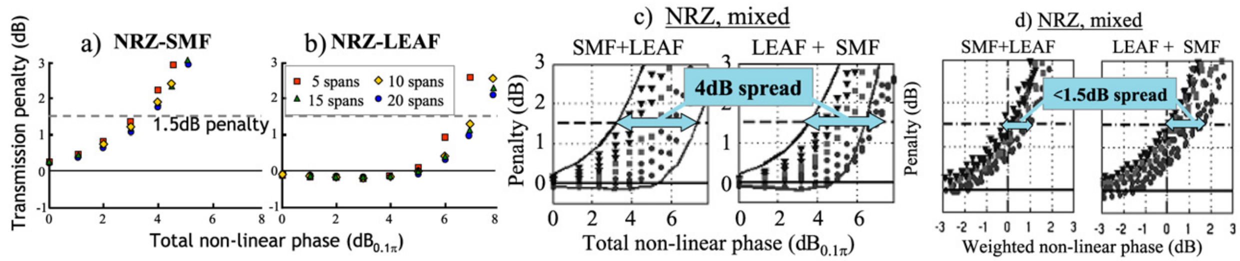

Fig. 14. (a) and (b) plots: penalty vs. total non-linear phase, for SMF (a) and LEAF (b) homogeneous systems, w/doubly periodic disp. maps. Various distances within [5; 20] spans, powers within [−10; +10] dBm. NRZ format, 40 Gb/s. (c) Penalty for mixed SMF/LEAF system consisting of concatenations of subsystems of (a) and (b), vs. total non-linear phase. (d) Evolution of penalty for mixed SMF/LEAF system, vs. weighted non-linear phase.

5.1. System under study

We define a homogeneous (sub-) system as a transmission (sub-) system involving only one line fiber type. By contrast, we define a heterogeneous, or mixed system, as a transmission system involving at least two different line fiber types, and thus composed of the concatenation of at least two homogeneous subsystems. The mixed system under study here is here composed of the concatenation of two homogeneous subsystems, each involving either SMF or LEAF line fiber and a doubly-periodic dispersion map, with zero residual dispersion per subdivision or 5 spans, as illustrated by Fig. 13. The number of subdivisions for each subsystem is varied, enabling distances up to 30×100 km, as well as the input powers into line fiber spans within [−10; +10] dBm, and the subsystem arrangement (SMF then LEAF subsystems, or LEAF, then SMF subsystems). Typical residual dispersion per span is set to 50 ps/nm, while Pre-compensation into each subsystem is optimized for the homogeneous propagation. At receiver end, post-compensation DCF is optimized on a per channel basis. NRZ is considered here for single-channel 40 Gb/s simulations. All these investigated configurations amounted to a total of over 50 000 simulations runs.

5.2. 40 Gb/s systems with two line fiber types

We first emulate homogeneous systems based on LEAF or SMF fiber, then heterogeneous systems mixing the two line fiber types. Fig. 14(a), (b) represents the computed penalties of reference homogeneous transmission configurations, for LEAF, or for SMF systems, as a function of total cumulated non-linear phase. For each fiber type, the tolerance to non-linearities is assessed thanks to the non-linear threshold (NLT), leading to a reference 1.5 dB penalty (corresponding to the maximization of reach for homogeneous LEAF or SMF systems, with a BER of 10^{-5}, as explained in Section 4.2.1). We can observe that the relationship between penalty and non-linear phase is almost bi-univocal regardless of distances and power, in agreement with [6,7], with a spread of the total non-linear phases corresponding to 1.5 dB-penalty lower than 0.4 dB for SMF and 0.8 dB for LEAF systems. The minimum NLT (mNLT) value, ensuring penalty lower than the reference in all conditions, corresponds to short transmissions over a single 5-spans subdivision, respectively at 3.2 $dB_{0.1\pi}$ (= 0.66 rad) for SMF and 6.4 $dB_{0.1\pi}$ (= 1.37 rad) for LEAF-based homogeneous systems. By convention, a non-linear phase of x rad, expressed in $dB_{0.1\pi}$ scale is defined as $10\log_{10}(x_{\mathrm{rad}}/0.1\pi)$.

Fig. 14(c) represents all the computed transmission penalties of NRZ-heterogeneous LEAF/SMF systems, such as those mentioned above. As already observed [7] at 10 Gb/s, performance of heterogeneous systems based on a combination of different line fiber types almost always lies in between the performance of the corresponding homogeneous systems based on those line fiber types (full lines), for a given total non-linear phase. Across all mixed systems, the spread of total non-linear phases corresponding to 1.5 dB-penalty is found as large as 4 dB, with values between 3.2 $\mathrm{dB}_{0.1\pi}$ and 7.2 $\mathrm{dB}_{0.1\pi}$. In [7], we proposed a first order approximation to determine the non-linear estimator as a function of the contributions of the different subsystems: we proposed to sum the contributions to non-linear phase $\Phi_{NL,A}$, resp. $\Phi_{NL,B}$ coming from each subsystem A resp. B, weighted by their own tolerance to non-linearities (i.e. minimum non-linear threshold mNLT_A, resp. mNLT_B at a given reference penalty, e.g. at 1.5 dB here), leading to a new variable called weighted non-linear phase:

$$\Phi_W = \frac{\Phi_{NL,A}}{\mathrm{mNLT}_A} + \frac{\Phi_{NL,B}}{\mathrm{mNLT}_B} \tag{19}$$

If the whole system is homogeneous, based on a single line fiber type, A or B, the penalty is lower than the 1.5 dB reference provided that the total non-linear phase is lower than the minimum non-linear threshold of this subsystem, thus as long as the weighted non-linear phase ϕ_W is lower than 1 (i.e. 0 dB when converted in dB scale). By analogy with the definition of the NLT for homogenous systems, we can define the *Weighted Non-Linear Threshold* (WNLT) as the value of ϕ_W yielding the same reference 1.5 dB penalty, and we expect it to remain close to 0 dB for heterogeneous systems. Under such assumptions, we can easily derive the expected total non-linear phase corresponding to the reference penalty for the mixed system (still denoted as NLT in the following), as a function of the ratio α of the cumulated non-linear phase in one of the subsystems (e.g. subsystem A in our two-subsystems model) over total non-linear phase:

$$\mathrm{NLT}_{A+B}(\alpha) = \frac{1}{\frac{\alpha}{\mathrm{NLT}_A} + \frac{1-\alpha}{\mathrm{NLT}_B}}, \quad \text{with } \alpha := \frac{\Phi_{NL,A}}{\Phi_{NL,A} + \Phi_{NL,B}} \tag{20}$$

Such an expected NLT value thus varies in between the NLTs of pure systems A and B alone, depending on the relative amount of non-linearities in the different subsystems $A\&B$, in agreement with Fig. 14(c). Fig. 14(d) (right) shows the computed penalties of Fig. 14(c) but the x-axis has been converted into the weighted non-linear phase. It can be observed that the resulting weighted non-linear leading to 1.5 dB penalty for heterogeneous systems are equal or higher than 0 dB in all the investigated configurations. In other words, the feasibility of heterogeneous systems is very likely ensured with respect to non-linear issues provided that the weighted non-linear phase is lower than the weighted threshold of 0 dB. To get insight on the resulting benefits, it should be emphasized that, in an industrial environment, the feasibility of a light-path usually relies on the worst-case scenario. Hence, with the conventional non-linear phase, the feasibility would be stemming from that of the worst performing fiber, in absence of specific experimental or numerical trial. Although an expected 0 dB-weighted non-linear threshold appears also pessimistic with respect to actual system behavior, it always predicts (by construction) a better resistance to non-linear effect over the heterogeneous system than over the homogeneous system of the same length, based on the worst performing fiber. Hence, using the weighted non-linear phase instead of the non-linear phase alleviates the need for power margin provisioning and results in even fewer rejections of actually feasible systems. Additionally, Fig. 14 also shows that the spread of weighted non-linear threshold values is reduced to less than 1.5 dB where the spread of total non-linear phases corresponding to 1.5 dB-penalty was as high as 4 dB. The tolerance to non-linear effects is hence better assessed, which also results in fewer rejections of actually feasible systems. Similarly in [8], we observed for PSBT format, under the same conditions, a spread of total non-linear phases corresponding to 1.5 dB-penalty as large as 5 dB. Conversely; weighted non-linear threshold values were found equal to, or higher than 0 dB, with a reduced spread, as low as 2.5 dB. For DPSK formats, similar simulations enabled to show that the spread of total non-linear phases corresponding to 1.5 dB-penalty is as high as 1 dB, whereas weighted non-linear threshold values are higher than 0 dB, with a spread as low as 0.5 dB. Similarly, for 10 Gb/s NRZ systems with 50 GHz channel spacing, the spread of total non-linear phases corresponding to 2.5 dB-penalty (2.5 dB leading to the maximization of reach for homogeneous LEAF or SMF systems, with a BER of 10^{-5}, as explained in Section 4.2.1) is as high as 2.5 dB, whereas weighted non-linear threshold values at 2.5 dB-penalty were always found equal to or higher than −0.2 dB, quite close to the 0 dB expected target, with a spread as low as 1 dB.

5.3. Extension to multi-fiber links, and application to power setting, system reach

The use of the weighted non-linear approach can be easily extended to higher degrees of heterogeneities: if we consider a mixed system composed of concatenation of k homogeneous subsystems, the weighted non-linear phase becomes:

$$\Phi_w = \sum_{i=1-k} \frac{\Phi_i}{\mathrm{NLT}_i} \tag{21}$$

with ϕ_i being the cumulated non-linear phase over subsystem i, with non-linear threshold NLT_i. Preliminary simulations performed with three types of fiber ($D = 2, 4, 17$ ps/(nm/km)) confirmed the relevance of this approach, with found weighted non-linear threshold values always equal to or higher than 0 dB.

In summary, we carried out an extensive assessment of the accuracy of the weighted non-linear criterion for predicting the tolerance to non-linearities, over heterogeneous systems, over a wide range of mixed SMF/LEAF configurations at 10–40 Gb/s, for several modulation formats (NRZ, PSBT, DPSK), thus highlighting its high potential to easily design heterogeneous meshed networks with mixed fiber types. The application of the weighted non-linear phase concepts to the determination of optimal setting of fiber input powers and of system reach is straightforward, since the calculations and conclusions of Appendix A do not require that fiber sections NLTs be constant over a transmission link.

6. Conclusion

In this article, we presented the main issues of designing high-bit rate optical transmission systems impaired by Kerr non-linear effects, as well as the necessity to build reliable engineering rules so as to cope with system complexity, one step beyond the capacities of today's purely analytical reasoning. More particularly, we focused on the effective quantification of the accumulation of non-linearities in a dispersion-managed system, using linear combinations of the non-linear cumulated phase shift generated into each fiber section, and derived analytical expressions of the optimum fiber input power distribution and of the system reach in heterogeneous systems with mixed fiber types.

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Appendix A. From (weighted) non-linear phase concepts to power setting rules and reach estimation

This section proposes to optimize fiber input power distribution in a heterogeneous link where concepts of integrated power, non-linear phase or weighted non-linear phase are applicable. Let us consider a dispersion-managed heterogeneous system composed of N sections of fiber followed by an amplifier. Each fiber $i = 1, \ldots, N$ is characterized by the accumulated phase $\phi^{\circ}_{(i)}$ (non-linear phase or integrated power, i.e. fiber input power for one fiber section), by the signal to noise ratio $\mathrm{OSNR}^{\circ}_{(i)}$ (assuming no noise at section input) for a reference fiber input power P°, and by the non-linear threshold NLT_i (expressed in terms of integrated power or non-linear phase, with same convention as ϕ°) corresponding to its class (as defined in Section 4.2), for a reference penalty, thus corresponding to a required Signal to Noise Ratio S. Those fiber sections are alternatively made of line fiber sections or Dispersion Compensating Fibers, followed by an amplifier with a noise figure independent on input/output power. For each Dispersion Compensating Fiber, we consider a non-linear threshold identical to that of the preceding line fiber section to compensate for, in agreement with non-linear phase concepts. The degree of freedom for each fiber section is the input power P_i. Under those assumptions, we expect the OSNR at transmission end to be higher than S, and the sum of the phases of each section weighed by their NLT to be lower than 1. Noise and non-linear constraints can hence be expressed as:

$$\begin{cases} \frac{1}{\mathrm{OSNR}(N, P_1, \ldots, P_N)} = \sum_{i=1}^{N} \frac{1}{\mathrm{OSNR}^{\circ}_{(i)}} \frac{P^{\circ}}{P_i} \leqslant \frac{1}{S} \\ \tilde{\Phi}_{NL}(N, P_1, \ldots, P_N) = \sum_{i=1}^{N} \frac{\Phi^{\circ}_{(i)}}{\mathrm{NLT}_i} \frac{P_i}{P^{\circ}} \leqslant 1 \end{cases} \tag{22}$$

System optimization corresponds here to the find optimal set of fiber input powers ($P_{i=1\ldots N}$) to maximize N. Let propose the following changes of variables: for each $i = 1, \ldots, N$, we define $\bar{P}_i = P^\circ \sqrt{(\mathrm{NLT}_i S)/(\Phi^\circ_{(i)} \mathrm{SNR}^\circ_{(i)})}$ and $\bar{N}_i = \sqrt{\mathrm{NLT}_i/S} \cdot \sqrt{\mathrm{SNR}^\circ_{(i)}/\Phi^\circ_{(i)}}$, corresponding to the optimal power and maximum reach of an homogeneous (dispersion-managed) system characterized by all spans identical to spans (i), as mentioned in Section 4.2. We also define $y_i = P_i/\bar{P}_i$. Eqs. (22) can thus be rewritten as:

$$\begin{cases} H_1(N, \underline{y}) = \sum_{i=1}^{N} \frac{y_i}{\bar{N}_i} \leqslant 1 \\ H_2(N, \underline{y}) = \sum_{i=1}^{N} \frac{1}{\bar{N}_i y_i} \leqslant 1 \end{cases} \tag{23}$$

Let us eventually define

$$H(N, \underline{y}) = \frac{H_1(N, \underline{y}) + H_2(N, \underline{y})}{2} = \frac{1}{2} \sum_{i=1}^{N} \frac{1}{\bar{N}_i} \left(y_i + \frac{1}{y_i} \right)$$

By construction, as long as the transmission is feasible, we have: $H(N, \underline{y}) \leqslant 1$. Besides, for all $\underline{y}$, $H(N, \underline{y}) \geqslant \sum_{i=1}^{N} \frac{1}{\bar{N}_i}$, with equality between both terms when $\underline{y} = (y_1, \ldots, y_n) = (1, \ldots, 1)$. Let us now define $N_{\max}$ as:

$$N_{\max} = \mathrm{Max} \left\{ N \text{ such as } \sum_{i=1}^{N} \frac{1}{\bar{N}_i} \leqslant 1 \right\} \tag{24}$$

The number of fiber sections N cannot be higher than $N_{\max}$, otherwise $H(N, \underline{y}) > 1$, which would mean that the transmission is not feasible. Conversely, for all N lower or equal to $N_{\max}$, then we can choose a set of normalized powers $\underline{y} = (y_1, \ldots, y_n) = (1, \ldots, 1)$, such that $H(N, \underline{y}) = H_1(N, \underline{y}) = H_2(N, \underline{y}) = \sum_{i=1}^{N} \frac{1}{\bar{N}_i} \leqslant 1$, which satisfies the feasibility criteria. It can be noted that in doing so, the noise-related (H_1) and non-linear (H_2) constraints are identical. Then, the maximum reach of the system is actually equal to $N_{\max}$. Besides, the dimensionless vector $\underline{y} = (y_1, \ldots, y_n) = (1, \ldots, 1)$ is the one enabling the longest reach.

If we look back at our transmission system, the optimum combination of powers consists in setting the power of each fiber section in order to allow maximum reach of a virtual link composed only of a succession of this replicated section. With such a rule, non-linear and noise constraints become identical, and Eq. (24) guarantees the feasibility of the connexion. A practical application concerns transmission link with line fiber sections differentiated by their losses: following Eq. (16), x dB higher loss should result in a fiber input power increased by $x/2$ dB.

Acronyms

ASE: Amplified Spontaneous Emission noise
BER: Bit Error Rate
DCF: Dispersion Compensation Fiber
DPSK: Differential Phase Shift Keying
GVD: Group Velocity Dispersion, also referred to as Chromatic Dispersion
FWM: Four-Wave Mixing
LEAF: Large Effective Area Fiber (G655 type)
mNLT: Minimum Non-Linear Threshold
NLSE: Non-Linear Schrödinger Equation
NLT: Non-Linear Threshold
NRZ: Non-Return to Zero format
OSNR: Optical Signal to Noise Ratio
PIC: Phase to Intensity Conversion
PMD: Polarization Mode Dispersion
PSBT: Phase Shaped-Binary Transmission format
RZ: Return to Zero format
SMF: Standard Single Mode Fiber (G652)

SPM: Self-Phase Modulation
XPM: Cross-Phase Modulation
WDM: Wavelength Division Multiplexing
WNLT: Weighted Non-Linear Threshold

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